FINAL REPORT

Title: Goats, Smoke, and Oaks: Prescriptive goat browsing and prescribed fire as a means to halt mesophication and promote biodiversity in Ozark Hardwood Ecosystems

JFSP PROJECT ID: 20-1-01-14

October 2021

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Abstract

In this study, we examined and compared the separate and combined effects of targeted browsing and prescribed burning on tree reproduction densities, fuel loading, and plant functional group composition. Frequent, low-intensity disturbances can aid in achieving woodland management objectives such as reduction of fuel loading, reducing stem densities of fire-intolerant tree species, and increasing the abundance and diversity of herbaceous ground flora. Prescribed burns are often used to meet these objectives; however, the prescribed fire use can be limited by many constraints (e.g., risk, smoke, legal), especially in association with the wildland-urban interface. Targeted browsing may provide a novel approach to mimic or supplement prescribed burning including extending the within-year disturbance window. The fire and compounding browse-fire treatments resulted in reduced midstory tree reproduction densities and the browse-fire treatment significantly reduced midstory eastern redcedar stems. The browse treatment did not affect tree reproduction densities. All treatments showed trends in reduced coverage of woody species with increases in the coverage of herbaceous species. However, the compounding browse-fire disturbance did not result in a greater response from ground flora in comparison to a single disturbance. The prescribed fire treatment significantly reduced litter but there were no differences detected for other fuel classes. Targeted browsing and the interaction of browsing and burning have the potential to increase herbaceous cover in Missouri Ozark woodlands. However, fire is likely necessary to reduce the density of small woody stems. Both the fire and browse-fire treatments were effective at reducing tree reproduction. Further, although burning may reduce litter, a single prescribed fire or targeted browsing event did not have significant influence on overall fuel loads.

1. Objectives

This study investigated four treatments: (1) a spring browse (peak growing season disturbance), (2) a prescribed fire (dormant season disturbance), (3) a spring browse + prescribed fire (compounding disturbance), and (4) an untreated control.

2. Background

Similarities between herbivory and fire effects on the landscape are widespread and numerous(Bond 2005). Both are plant-consuming disturbances that have played critical roles in forming the structure and function of woodlands by altering long-term patterns in plant community composition (Churski et al. 2017). Oak woodlands are open-structured forests defined by overstory canopy conditions that range from 30-80% cover, a minimal midstory vegetation layer, and an overstory dominated by oak species (Nelson 2005). Woodlands commonly have dense, species-rich ground floras dominated by herbaceous functional groups with increased graminoid cover as tree canopy cover decreases (Nelson 2005). Prescribed fire in a common technique to reduce surface fuel loading, limit the encroachment of woody stems, and increase the abundance and diversity of herbaceous ground flora (Brose et al. 2013; Maginel et al. 2016; Knapp et al. 2017). However, socio-political factors can limit the use of fire (e.g., risk to infrastructure, human health and safety, plant phenology). Targeted herbivory may offer a unique approach to reach woodland management objectives while targeted herbivory in concert with prescribed fire may speed restoration efforts. It is not well understood how tree genera respond to targeted herbivory nor how targeted herbivory effects ground flora or fuel loading, particularly in eastern U.S. woodlands.

Targeted herbivory (browsing or grazing, depending on livestock) can be defined as a controlled disturbance regime that integrates the seasonality, frequency, duration, and intensity of herbivory events with elements of animal science and plant ecology to achieve desired plant community composition and structure (Bailey et al. 2019). Specifically, goats were chosen as the livestock in this study because of their ability to consume a widely varied diet but preference to consume lignified species (i.e., intermediate feeders). Goats can also stand on hind legs, increasing their browse reach to approximately 2 m, which is effective for defoliating small trees, shrubs, and lower canopy portions of midstory trees (referred to as ‘targeted goat browsing’ hereafter).

A substantial body of research has shown prescribed fire and targeted herbivory reduce the density of woody stems (Harrington and Kathol 2009; Brose et al. 2013; Knapp et al. 2017) and increase herbaceous species cover (Augustine and McNaughton 1998; Raffaele et al. 2011; Maginel et al. 2019). Though studies on interactive effects of fire and targeted herbivory in the U.S. are sparse, studies describing fire-thinning disturbances or fire-grazing disturbances in other countries show that a compounding disturbance can result in greater herbaceous species cover and greater reduction in woody stem densities than either disturbance alone (Staver et al. 2009; Raffaele et al. 2011; Vander Yacht et al. 2020). This raises questions about whether fire in combination with targeted herbivory can generate a stronger response from ground flora than either disturbance alone. However, plant characteristics and life history traits may play a large role in plant response to herbivory and fire. For example, white ash (*Fraxinus americana* L.) and red maple (*Acer rubrum* L.) are considered fire-sensitive species (Taft 2003) while oaks (*Quercus* spp.) are considered fire-tolerant species (Johnson et al. 2009). On the other hand, red maple was found to be moderately browse-sensitive while white ash, black gum (*Nyssa sylvatica* Marshall), and pawpaw (*Asimina triloba* L.) were found to be relatively browse-tolerant (Krueger et al. 2009; Bressette et al. 2012). With repeated fire or herbivory disturbances, the species composition of the landscape may change based on tolerances to these disturbances.

Surface fuels management plays an important role in fire management to reduce risk to communities and infrastructure (Andrews and Butler 2006). While prescribed fire is a commonly suggested method of fuels management to reduce fuel depths and fine-fuel loading (Kolaks et al. 2004), targeted goat browsing offers another approach to fuels management with limited risk to infrastructure and little need to consider unfavorable microclimatic or weather-related conditions (i.e., some of the constraints associated with prescribed fire). Specifically, targeted goat browsing is effective at reducing vertical and horizontal fuels continuity, creating fire breaks, and potentially reducing the need for recurring surface fuels management (Papachristou et al. 2005; Lovreglio et al. 2014; Manousidis et al. 2016). Goat browsing can reduce the density and mean height of live fuels (Mancilla-Leytón and Martín Vicente 2012) and fine-fuel loading (Fleischner 1994; Lempesi et al. 2013; Lovreglio et al. 2014) with reductions to their impact on heavy fuels (e.g., > 100-hour fuels) being limited (Tsiouvaras et al. 1989). Goats' capacity to reduce litter fuel depths is mainly through trampling whereby fuels are crushed, fragmented, and incorporated into soils, reducing the likelihood of ignition (Lovreglio et al. 2014).

To better compare fire and targeted browsing disturbances, this study was designed as an experimental approach to investigate their distinct and interactive effects on woody stem densities, coverage of plant functional groups, and fuel loading. This study consisted of four treatments: 1) a spring browse treatment (growing season disturbance), 2) a low-intensity dormant season prescribed fire, 3) a spring browse + dormant season prescribed fire treatment (compounding disturbance; two disturbances per experimental unit), and 4) a control. The spring browse and prescribed fire treatment allowed for direct comparison between browsing and burning. The compounding browse + fire treatment was designed to test for an interactive effect. We predicted that: 1) tree reproduction densities would decrease following treatments; 2) treatments would decrease woody species cover (trees, shrubs, and woody vines) and increase herbaceous species cover (forbs, grasses, sedges, and legumes); 3) treatments would reduce fine fuel loading and decrease litter depths; and 4) the compounding browse-fire treatment would have a stronger effect on tree reproduction, functional group cover, and fuel loading than either disturbance alone.

3. Material and Methods

This research study occurred on the Houston/Rolla/Cedar Creek District of the United States Department of Agriculture (USDA) Forest Service, Mark Twain National Forest (MTNF) (37.892778, -92.018333). This study is located in the Ozark Highlands ecological section of the Ozark Broadleaf Forest (Bailey 1995). Karst topography and its features are a defining characteristic of the Ozark Highlands (McNab and Avers 1994). Elevation was approximately 300 m above sea level and slopes ranged from 1 to 25%. Sandstone and dolomite parent materials underlie Ultisols and Alfisols formed from hillslope sediment, residuum, and loess (Soil Survey Staff 2019). Mean annual temperature is 13.1°C and the average daily temperature in January is -2.2°C and in July is 23.3°C. The climate record period from 1888 to 2021 shows the mean annual precipitation is 1226 mm and May, on average, has the greatest precipitation (NOAA 2021).

Onyx Cave, a hibernacula for multiple bat species, is located 1 km away from the study area. To improve foraging habitat for bats, woodland structure was created at this site in 2012 by thinning trees < 23 cm dbh, (target residual basal area was 16.1 to 18.4 m^2 ha^{-1}). The area was masticated in 2017 to improve the woodland structure thereby reducing midstory woody encroachment and encouraging herbaceous understory growth. The management plan for the site does not include herbicide (due to karst topography) nor prescribed fire due to proximity to an interstate highway (0.5 km east) and for smoke and lack of visibility. Concerns for the expense of repeated mastication to maintain woodland structure for wildlife habitat and the social limitations for prescribed burning were primary factors that led to the development of this study.

From forest inventory data collected in 2019, the average stocking across the study site was approximately 85% (Gingrich 1967). Overstory trees per hectare (TPH) ranged from 183 to 246 and basal area (BA) ranged from 12.6 to 16.6 $m^2\ ha^{-1}$. Common overstory tree species include white oak (*Quercus alba* L.), post oak (*Q. stellata* Wangenh.), and black oak (*Q. velutina* Lam.). Many overstory trees express architecture of past open woodland conditions including large, spreading crowns and low, persistent primary branches. Common midstory tree and shrub species include black hickory (*Carya texana* Buckley), wild plum (*Prunus americana* Marshall), fragrant sumac (*Rhus aromatica* Aiton), and blackberries (*Rubus* spp.). The most abundant forb species in the understory include burnweed (*Erechtites hieraciifolius* L.), oblong sunflower (*Helianthus hirsutus* Raf.), and elm-leaved goldenrod (*Solidago ulmifolia* Muhl. ex Willd). The most abundant legumes were hog peanut (*Amphicarpaea bracteate* L.*)* and small-leaved tick trefoil (*Desmodium marilandicum* L.). Graminoids were primarily composed of poverty oats grass (*Danthonia spicata* L.), panic grasses (*Dichanthelium* spp.), broom sedge (*Andropogon virginicus* L.), and fuzzy wuzzy sedge (*Carex hirsutella* Mack.).

Permanent vegetation plots were established in February 2019. Within each 0.08 ha plot, trees $\geq$ to 3.8 cm dbh (1.37 m) were inventoried. Four 3.6 m radius subplots were nested within the larger plot where trees $\geq$ 1 m tall and < 3.8 cm dbh ('midstory' trees hereafter) were inventoried by species. Within each subplot, four 1-m^2 quadrats were established at each cardinal direction from subplot center (0°, 90°, 180°, and 270°) for a total of 16 quadrats per plot. In each quadrat, trees < 1 m tall ('understory' trees, hereafter) were inventoried by species. Additionally, the percent ground cover of bare soil, disturbed soil, litter, and functional group (forb, grass, sedge, legume, fern, shrub, tree, and vine) was recorded in each quadrat. The percent cover of functional groups was recorded from 0-2 m above ground-level. The cover of each functional group was estimated independently, and total estimations could go above 100%. Due to low coverage, rushes were recorded within the sedge functional group.

In fall 2020 (October-December), we measured fuels using four modified Brown's fuel transects per plot (Brown et al. 1982) at the following azimuths from plot center: northeast (45°), southeast (135°), southwest (225°), and northwest (315°; Figure 1). Each transect was 15.2 m long. Along the entire length of the transect, diameter, species, and decay class (sound or rotten) was recorded for 1000-hour downed woody debris. Decay class followed Brown et al. (1982); sound wood held its shape whereas rotten wood sloughed or compressed when kicked or pierced with a pen. At 3.1 m, 6.1 m, and 9.0 m along each transect, the depth of litter and duff was measured to the nearest 0.25 cm for a total of 12 depth readings per plot (Figure 1). Additionally, because the site had been masticated, six fuel samples were collected and bagged per plot. Fuel samples were collected 5 m from each subplot center (Figure 1). A 0.25 m x 0.25 m quadrat was laid on the ground and fine fuel loads (litter, bark, 1-, 10-, and 100-hour fuels) within the quadrat was collected. Fuels were dried in ovens for 48 hours at 80° C or until a constant weight was achieved. Fuels were then sorted by litter, bark, and fuel class and weighed.

Due to the timing of the spring browse treatment, pre-treatment data collection for woody species and bare and disturbed soil impacts in the spring browse and spring browse + prescribed fire treatments occurred just prior to the browse treatment in the April 2019. This resulted in data being collected prior to leaf-out and functional group cover was not recorded due to minimal plant emergence. Pre-treatment data for all other treatments was collected in summer 2019 (May-

August), during peak growing season conditions. All post-treatment sampling occurred in summer 2020 (May-July).

This experiment was conducted as randomized complete block design with four treatments, each with three replications (n = 12). Each experimental unit was between 1- and 3.2-hectares in size. Browsing treatments occurred in May 2019 using a mixture of different meat goat breeds. The herd consisted of approximately 135 nursing nanny goats and kids. Due to variability in treatment unit size, a browsing threshold was established to maintain a consistent final browsing level across all replications. When approximately 85% of all vegetation was browsed across the unit, goats were removed. Browsing thresholds were met in 3 to 5 days following entry.

Prescribed fires occurred prior to leaf-out on two separate days in February 2020. A total of 9.4 ha were burned using hand-lit strip fires to meet the objectives of a low-intensity fire. Fuels mainly consisted of leaf litter, 1-hour fuels, 10-hour fuels, and dried warm season grasses. Flame lengths recorded by observers averaged between 0.3-0.6 m. The highest daily ambient air temperatures ranged between 12-20°C. Average wind speeds ranged from 18.1-20.3 kmh. Relative humidity ranged between 25-30%. Fire burn coverage was patchy and primarily consumed litter and grasses with overall woody fuel consumption declining with time-lag class, We estimated fire temperature at plots using Tempilaq brand temperature-sensitive paints applied to aluminum tags with melting temperatures of 77°C, 121°C, 149°C, 177°C, 204°C, 232°C, 260°C, 288°C, 343°C, or 399°C. Tags were hung on wire pins at 15 cm above the litter layer at the center of each 0.08-ha plot and 0.004-ha subplot, resulting in 20 tags per experimental unit. The highest melted temperature-sensitive paint was recorded as the temperature of the fire at the location of the tag.

Average fire temperature was determined for each plot by calculating the mean temperature of each of the five paint tags and, subsequently, averaged for each treatment. There were 19 tags in the prescribed fire treatment and 18 tags in the spring browse + prescribed fire treatment that did not burn (unmelted paint), totaling 37 unburned tags. To better understand fire effects on research objectives, unburned tags were removed from fire temperature calculations and all analyses.

To examine treatment effect on the change in midstory and understory trees per hectare (TPH), we used ANOVA models with treatment as independent variables and the change in TPH as dependent variables (calculated as the difference between post- and pre-treatment TPH). We counted only the main stem and not the sprouts in these density analyses. Further, we separated the data into species groups based on Hahn and Hansen (1991), resulting in ten categories: cherries (wild plum, black cherry [*Prunus serotina* Ehrh.]), dogwoods (flowering dogwood [*Cornus florida*, L.]), eastern redcedar (*Juniperus virginiana* L.), elm-hackberries (slippery elm [*Ulmus rubra* Muhl.], common hackberry [*Celtis occidentalis* L.]), hickories (black hickory, mockernut hickory [*Carya. tomentosa* Lam.]), maples (red maple), other hardwoods (black gum, Carolina buckthorn [*Frangula caroliniana* A. Gray], serviceberry [*Amelanchier arborea* Michx. f.], pawpaw, eastern redbud [*Cercis canadensis* L.], persimmon [*Diospyros virginiana* L.], sassafras [*Sassafras albidum* Nutt]), red oaks (black oak, blackjack oak [*Q. marilandica* Münchh.]), white ash, and white oaks (white oak and post oak). We used an ANOVA model with treatment, species group, and the interaction of treatment and species group to determine differences between species groups. To examine the effect of the treatment on the change in stem densities within a species group for both mid- and understory densities, we then created separate ANOVA models for each species group with treatment as an independent variable.

To compare treatment effects on functional groups, we used post-treatment data only and compared those outcomes to the control due to a lack of representative pre-treatment ground flora data for the spring browse and spring browse + prescribed fire treatments. For the functional group coverage analysis, a separate ANOVA model was developed for each functional group. The fern functional group was removed from this analysis due to too few samples. Further, to illustrate deviations in functional coverage from the control, we used an effect size comparison (Cohen's d; Cohen 2013), standardizing treatment effects to the control for each of the seven functional groups. We also compared an 'all treatments' category (average of all treatments) to the control to further our understanding on the role of disturbance in shaping functional group composition.

To examine the effects of treatment on the coverage of bare soil, disturbed soil, and litter we used a repeated-measure ANOVA model to test for treatment (spring browse, prescribed fire, spring browse + prescribed fire, control) and sampling period (pre-treatment, post-treatment) effects for each dependent variable (percent cover of bare soil, disturbed soil, and litter).

For fuel weights and depth analyses, all treatments were compared to the control because we did not have pre-treatment fuels data. Weights and depths of fuels were averaged to the experimental unit. For each dependent variable (weights: litter, bark, 1-, 10-, 100-, 100-hour fuels; depths: litter and duff), we used an ANOVA model with treatment and time since treatment as independent variables. Time since treatment was calculated as the number of months since the most recent treatment and was 0 months for the control, 16 months for the spring browse, 8 months for the prescribed fire, and 8 months for the spring browse + prescribed fire treatment. For 1000-hour fuels, we used the following calculation (Brown et al. 1982) to determine tons acre^{-1} for each transect:

$$\frac{tons}{acre} = \frac{11.64 \times \sum d^2 \times \mathrm{s} \times \mathrm{a} \times \mathrm{c}}{L}$$

Where 11.64 is the conversion factor from debris volume to tons acre^{-1}; d is the diameter of downed woody debris; s is the specific gravity of fuels (0.3 for rotten debris and 0.4 or sound debris); a is the non-horizontal angle factor correction factor (a = 1), c is the slope correction factor (c = 1); L is the length (ft) of the transect (L = 50 ft.). We converted tons acre^{-1} to kg ha^{-1} and averaged fuel area densities to the experimental unit.

Subplots where temperature-sensitive paints did not melt were removed from all analyses. For analysis, all data were averaged to the experimental unit level. All statistical analyses performed using `R 4.1.0` (Core Team 2020) with significance determined at an alpha of less than 0.05. All normality parameters were based on the Shapiro-Wilks normality test. For significant effects, we used Tukey's Honestly Significant Difference (HSD) to determine pairwise differences between each treatment.

4. Results and Discussion

Fire temperature

The average fire temperate was 157 ± 5.7°C in the prescribed burn treatments and 173 ± 6.8°C in the spring browse + prescribed fire treatments. The highest temperature recorded on any individual aluminum tag was 343°C.

Browsing and fire effects on woody stem densities

For change in midstory stem densities by treatment alone, treatment was significant ($F_{3,96} = 9.9$, $p < 0.001$; Table 1). Midstory stems declined more in the prescribed fire and spring browse + prescribed fire treatments than in the spring browse or control treatments. For change in stem density by species group, treatment was significant ($F_{3,61} = 9.6$, $p < 0.001$) while neither species group ($F_{9,61} = 1.0$, $p = 0.46$) nor the interaction of treatment and species group ($F_{26,61} = 0.9$, $p = 6.2$) were significant (Figure 2). Within each species group, treatment was only significant ($F_{3,6} = 11.7$, $p < 0.006$) for eastern redcedar and stems declined more in the browse-fire treatment compared to all other treatments. Generally, the TPH of almost all species declined or stayed similar following fire treatments (Figure 2).

For change in understory stem density by treatment, treatment was not significant ($F_{3,112} = 0.8$, $p = 0.48$; Table 1). For change in understory stem density by species group, neither treatment ($F = 1.2$, $p = 0.33$) nor species group ($F = 1.5$, $p = 0.14$) was significant, however, their interaction was ($F_{3,76} = 2.4$, $p = 0.0014$; **Error! Reference source not found.**2). Treatment was significant for other hardwoods ($F_{3,8} = 4.1$, $p = 0.048$) and increased more in the spring browse + prescribed fire treatment compared to the spring browse treatment.

Trends in the coverage of functional groups

Treatment was not significant for any functional group. However, there was a broad increase in the percent cover of nearly every functional group pre- to post-treatment, including in the control (Appendix A). The effect size comparison (Figure 3) determined that grass cover increased significantly in the browse treatment, tree reproduction cover decreased significantly in the prescribed fire treatment, and forb cover increased significantly in both the prescribed fire and browse-fire treatments (Appendix B).

Browsing and fire effects on ground coverage and fuel loading

Both treatment ($F_{3,16} = 14.9$, $p < 0.001$) and sampling period ($F_{1,16} = 59.8$, $p < 0.001$) were significant for bare soil cover. Bare soil cover was greater post-treatment and in the prescribed fire treatment compared to the control (Figure 4). For disturbed soil cover, treatment was not significant ($F_{3,16} = 2.8$, $p = 0.07$), but sampling period was ($F_{1,16} = 24.4$, $p < 0.001$) and was greater post-treatment (Figure 4). For the litter cover, both treatment ($F_{3,16}$ = 4.3, p = 0.018) and sampling period were significant ($F_{1,16}$ = 14.8, p = 0.001). Litter cover was lower post-treatment and in the spring browse + prescribed fire treatment compared to control (Figure 4).

For the weight of litter, treatment ($F_{1,10}$ = 12.3; p = 0.001) was significant whereas time since treatment was not ($F_{1,10}$ = 4.3; p = 0.065). There was significantly more litter in the control compared to both the prescribed fire and the browse-fire treatments. Further, there was significantly more litter in the spring browse treatment compared to the prescribed burn treatment (Table 2). Treatment was not significant for any other fine fuel loads nor was it significant for fuel depths.

Low-intensity disturbances are key to restoring or maintaining woodland conditions (i.e., limiting woody stem encroachment in the midstory and promoting a dense, herbecous ground flora) and for managing fuel loads (Kolaks et al. 2004; Brose et al. 2013; Knapp et al. 2017; Maginel et al. 2019). While prescribed fire is commonly used and effective at achieving desired woodland management objectives, its use can be limited by seasonality or plant phenology, risk to infrastructure, and human health and safety. Targeted goat browsing has the capacity to achieve common woodland management objectives and may offer land managers a supplemental approach to prescribed fire while the interactive effects of browsing and fire may speed restoration efforts by eliciting a stronger reduction in stem densities and a greater response from ground flora. There are limited comparative studies examining the effects of targeted goat browsing and prescribed fire in woodland ecosystems and this research may provide a new management strategy for the restoration of fire-dependent ecosystems.

We sought to determine how targeted goat browsing individually and combined with prescribed fire effect stem densities, functional group cover, and fuel loading in Ozark woodlands. We concluded that fire was more effective than browsing at reducing midstory stem densities and may suggest that most midstory tree species groups are more tolerant to a single browse disturbance than to a single fire disturbance. Understory stem densities increased following all treatments and density trends among species groups were variable. General trends in functional groups included increased herbaceous species cover (forbs, grasses, sedges; minimal change in legumes) and decreased woody species cover (trees, woody vines, and shrubs). Overall, treatments did not greatly impact fuel loads though the fire and browse-fire treatment significantly reduced litter weights.

Contrary to predictions and the results of other studies (Harrington and Kathol 2009; Churski et al. 2017), mid- and understory stem densities of almost all species groups trended upward in the browse treatment. Our results indicate that, regardless of browse tolerance, a single browsing event will probably not reduce stem densities significantly and repeated browsing disturbances will likely be needed. This conclusion is substantiated by Harrington and Kathol (2009) who determined that after a single treatment of cattle grazing, no difference in stem densities could be determined between grazed and ungrazed plots. However, stem densities decreased by 44% after a second treatment of cattle grazing.

As predicted, midstory stem densities of all species groups trended downward in the fire and browse-fire treatments. Although there was not a significant difference between the fire and browse-fire treatments, overall midstory stem densities were the lowest in the browse-fire treatment. This may indicate that prescribed fire, following targeted browsing pressure, may result in an interactive reduction in midstory stems. This effect may become more pronounced with repeated treatments as other studies have suggested a similar result (Midgley et al. 2010). For example, Staver et al. (2009) concluded that the impact of browsing in addition to fire limited tree reproduction more than the combined effects of either disturbance alone. Additionally, the browse-fire treatment resulted in a significant reduction in midstory eastern redcedar stems. While it known that eastern redcedar is a fire-sensitive species (Anderson 2003), the preceding browsing pressure reduced the density more than fire alone. Based on visual observations, goats consumed both the foliage and bark of eastern redcedar, stripping bark sometimes as high as 2 m up. This result may be of particular interest to managers of glades or prairies where removal of eastern redcedar is a common objective.

The response of understory stem densities in the fire and browse-fire treatments was more variable and trends among species groups were not clear. Results show that there was a significant increase in other hardwood stem densities in the browse-fire treatment. To the contrary, other hardwood stems decreased in the fire treatment. Based on field observations, we surmise that overall treatment effects may be due to top-killed individuals resprouting into smaller height classes as well as the varying sprouting capacity of species groups (Knapp et al. 2021). However, we did not track individual trees so individual responses to treatments, such as being top-killed or fully killed, could not be quantified.

Forb cover increased significantly in the two fire treatments but did not increase significantly in the browse treatment. This suggests that fire elicits a stronger response from forbs in comparison to a single browse disturbance. However, the prescribed fire occurred in winter when forbs were mostly dormant whereas the browse disturbance occurred in late spring when many forbs were flowering. This interaction of plant phenology and seasonality of disturbance may have affected forb response (Hadar et al. 1999). Longer-term monitoring and repeated browse disturbances are needed to fully understand the effect of browsing on forb cover. Further, the compounding browse-fire disturbance did not result in greater forb cover than either disturbance alone which is in contrast to the findings of the limited comparative studies that have examined the interactive effects between herbivory and fire on forb cover. For example, Raffaele et al. (2011)found that the occurrence of cattle grazing increased forb cover, compared to no cattle grazing, following a wildlife in a beech forest in Patagonia.

The percent cover of grasses trended upward in all treatments but only significantly increased in the browse treatment. While grass cover has been negatively correlated to tree canopy cover (Peterson et al. 2007), tree reproduction cover did not decline significantly in the browse treatment. This may indicate that grass response is not directly associated with increased light availability. However, this result may also reflect the difference in cover between the first sampling period (summer 2019; one-month post-browsing disturbance) and grass cover recovery by the second sampling period (summer 2020; 13 months post-browsing disturbance). Results of these functional group analyses are based from data collection immediately following browsing or fire disturbances. Long-term patterns cannot be extrapolated and lag time response from functional groups cannot be considered.

Significant reductions in litter weights occurred in the fire and browse-fire treatments. Other studies have validated the finding that litter loading can be considerably reduced after a single prescribed fire (Kolaks et al. 2004; Knapp et al. 2011). Most litter inputs come from the overstory canopy whereas only a percentage of inputs are from the midstory canopy which is the target removal area of goats. Although not significant, the browse treatment had less litter than the control. This may suggest that with extended goat presence or multiple treatments per year, litter inputs may be reduced significantly.

Contrary to predictions, treatments did not impact 1-hour fuel loads. Other studies have determined that 1-hour fuel loads were reduced by pyric herbivory (i.e., free-roaming livestock in combination with prescribed fire; Starns et al. 2019) or by a single prescribed fire (Kolaks et al. 2004; Knapp et al. 2011) or goat browsing disturbance. For example, (Tsiouvaras et al. 1989) found that goats (present for 3 days at a stocking rate of 113 goats per acre) reduced 1-hour fuels by 58% in a California coastland plant community. This discrepensies in results between our study and Tsiouvaras et al. (1989) may be due to differences in stocking rate, browsing intensity, or fuel bed type. In our study, there were approximately 30 goats per acre and goats were present until vegetation conditions were met (which took 3-5 days), not neccesarily until fuel targets were met. Additionally, there is a masticated fuel bed at our study which may have significantly increased the amount of 1-hour fuels more than that which would naturally occur. Lack of significant treatment effects on fine fuel loading may be due, in part, to the patchy burn coverage of the prescribed fire. Lastly, our results determined that treatment had minimal impact on larger fuel loads (i.e., 100-hour and 1000-hour fuels). This result has been corroborated by other studies examining the impacts low-intensity fires and herbivory on fuel loads (Tsiouvaras et al. 1989; Kolaks et al. 2004).

5. Conclusions

Targeted goat browsing and the interaction of browsing and fire hold the potential to meet woodland restoration objectives in Missouri Ozark woodlands. Browsing tended to increase herbaceous species coverage while decreasing woody species coverage though the two fire prescriptions elicited a stronger and significant response from forbs. These short-term results suggest that browsing treatments may be viable for woodland flora restoration objectives and be an alternative to fire in areas where burning is not possible. We determined that our single browse disturbance was not intense enough to significantly alter tree reproduction densities. However, the fire and browse-fire treatments were effective at midstory stem reduction while the browse-fire treatment significantly reduced midstory eastern redcedar stems. Fuel loads were minimally altered by treatments with the main exception being that fire significantly reduced litter weights. Increased fire intensity along with repeated disturbances (both browsing and fire) may be needed to significantly affect overall stem densities, functional groups, or fuel loading. Although our results did not broadly indicate that the effects of the browse-fire disturbance were additive, research suggests the effects may be strongly interactive and if applied on the landscape over time and distinct patterns of change in species composition or woodland structure may emerge in comparison to a prescribed fire or targeted browsing treatment alone.

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Tables

Table 1. Midstory (trees > 1 m tall and < 3.8 cm dbh) and understory (trees < 1 m) trees per hectare (TPH), ± the standard error, in all treatments. Change is calculated as the difference between the average post-treatment and pre-treatment TPH. Letters (a, b) indicate significant ($p < 0.05$) differences in pairwise comparisons.

Treatment	**Pre-treatment TPH**	**Post-treatment TPH**	**Change**
	Midstory trees		
Control	865 ± 350	1,443 ± 501	578_a
Spring browse	588 ± 186	737 ± 201	149_a
Prescribed fire	1,100 ± 357	849 ± 360	-251_b
Spring browse + prescribed fire	1,658 ± 1,156	824 ± 309.6	-834_b
	Understory trees		
Control	13,854 ± 1,693	16,927 ± 994	3,073
Spring browse	12,604 ± 652	17,031 ± 3,611	4,531
Prescribed fire	11,198 ± 1,664	17,135 ± 376	5,937
Spring browse + prescribed fire	15,937 ± 2,127	18,593 ± 2,825	2,656

Table 2. Average weights (kg ha^{-1}) for each time lag class (1-hour, 10-hour, and 100-hour fuels), litter, and bark as well as the average depths (cm) for litter and duff ± the standard error. * indicate a significant treatment effect. Letters (a, ab, bc, c) indicate significant ($p < 0.05$) pairwise differences among treatments.

Fuel loading type	Control	Prescribed fire	Spring browse	Spring browse + prescribed fire
Litter* (kg ha^{-1})	1,960.3 ± 137$_{a}$	649.2 ± 63.5$_{c}$	1,469.0 ± 207$_{ab}$	1,155.7 ± 197$_{bc}$
Bark (kg ha^{-1})	329.2 ± 111.3	513.2 ± 196	489.4 ± 125	358.0 ± 79.7
1-hour (kg ha^{-1})	557.7 ± 18	578.6 ± 104	480.4 ± 22.0	455.3 ± 24
10-hour (kg ha^{-1})	1,129.3 ± 262	1,369.1 ± 92.4	1,036.0 ± 146	1,337.6 ± 102
100-hour (kg ha^{-1})	1,683.1 ± 800	1,449.8 ± 632.6	1,006.0 ± 245	1,129.3 ± 262
1000-hour (kg ha^{-1})	11,403.7 ± 327.4	9,104.2 ± 779.4	9,206.5 ± 868.2	21,613.3 ± 1153.2
Litter depth (cm)	8.68 ± 0.57	7.32 ± 0.33	8.05 ± 0.42	7.64 ± 0.58
Duff depth (cm)	0.63 ± 0.4	0.06 ± 0.03	0.07 ± 0.02	0.15 ± 0.08

Figure Captions

Figure 1. Vegetation and fuels data collection sampling design.

Figure 2. Change (difference between post- and pre-treatment sampling) in midstory (trees > 1 m tall ≤ 3.8 cm dbh; top) and understory (trees < 1 m tall; bottom) trees per hectare (TPH) by species group in each treatment. Letters (a, ab, b) above columns indicate significant differences in the TPH of species groups between treatments. Bars indicate standard error.

Figure 3. Effect size comparison of treatment on change (difference between post- and pre-treatment sapling) in percent cover for each functional group in the spring browse (SB), prescribed fire (Rx), spring browse + prescribed fire (SB & Rx) treatments, and the combined 'All Treatments' category (ALL). Cohen's d was determined as the difference between the control and treatments for each functional group. Symbols indicate the average Cohen's d value and bars denotes the 95% confidence interval. If the confidence interval crosses zero, then treatment effect is not statistically different from the control.

Figure 4. The percentage of ground covered by bare soil, disturbed soil, or litter in pre- or post-treatment conditions. Sampling period was significant for all ground coverage components, as indicated by the asterisk. Letters (a, ab, b) along the x-axis indicate significant differences in cover among treatments. Bars indicates standard error.

Figures

Figure 1

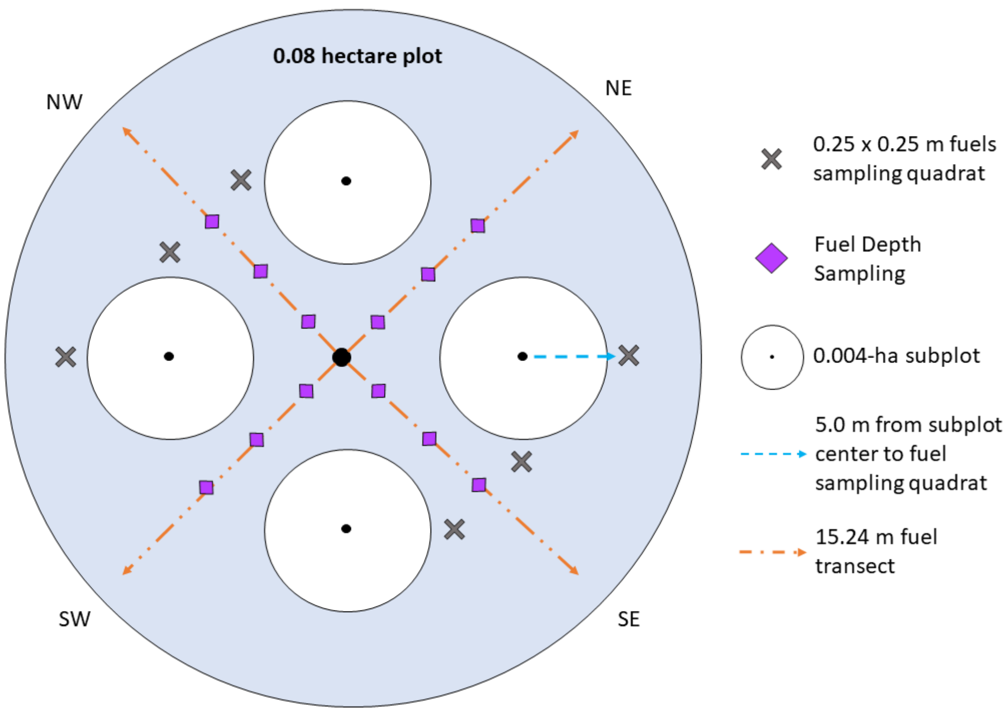
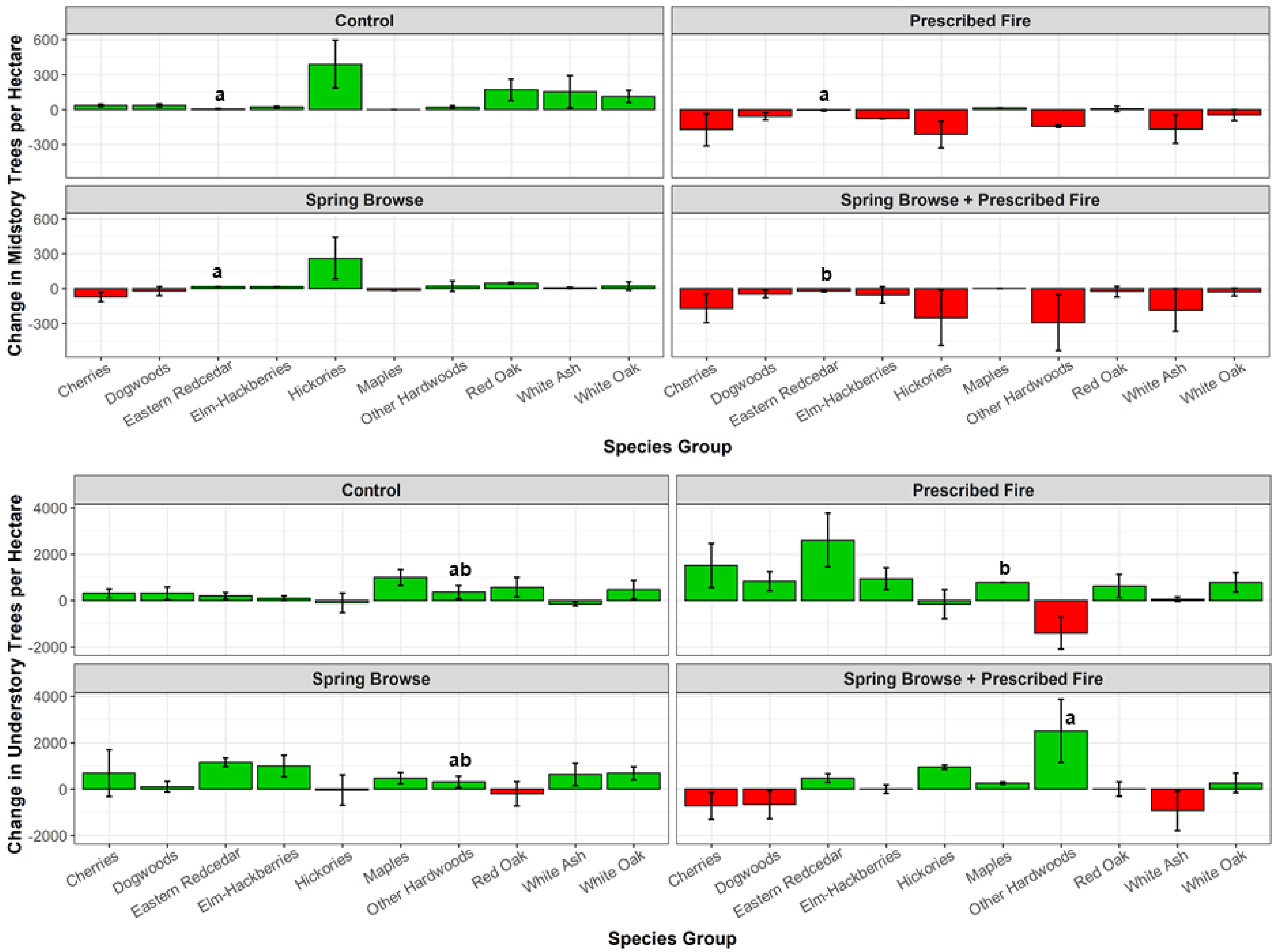
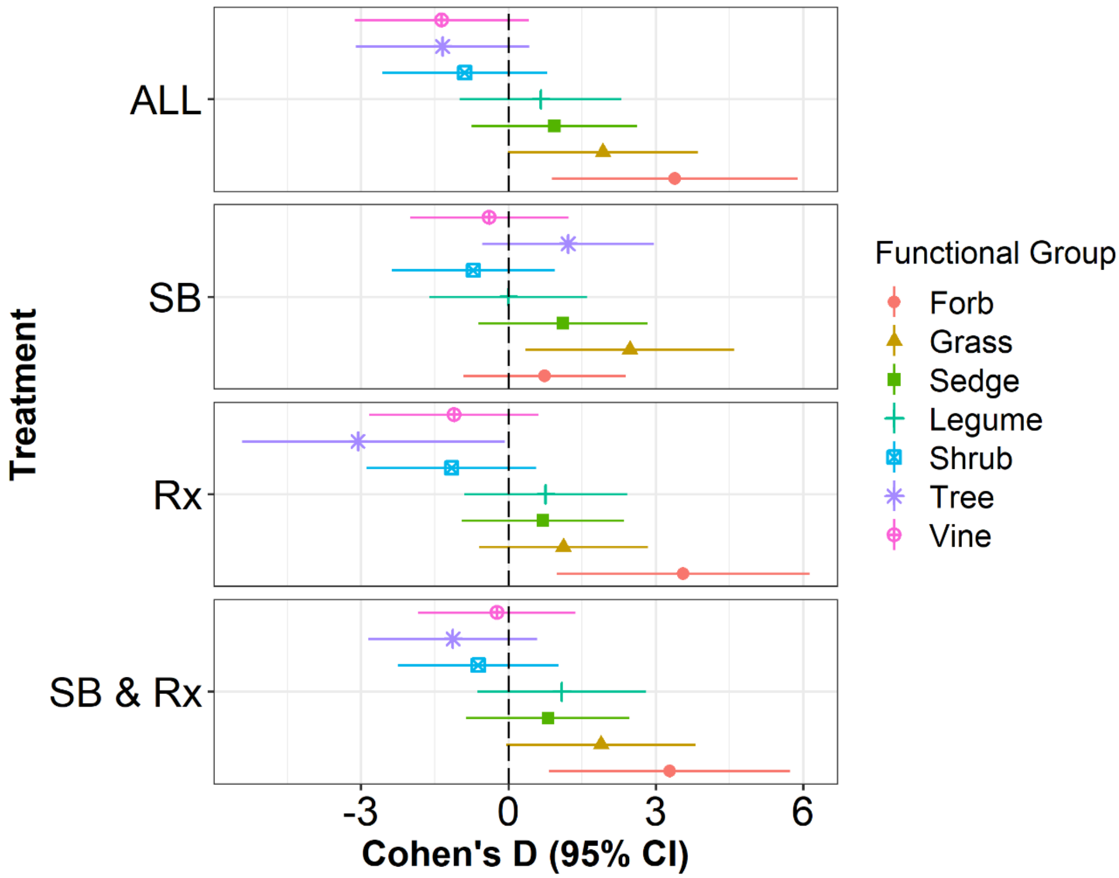


Figure 2



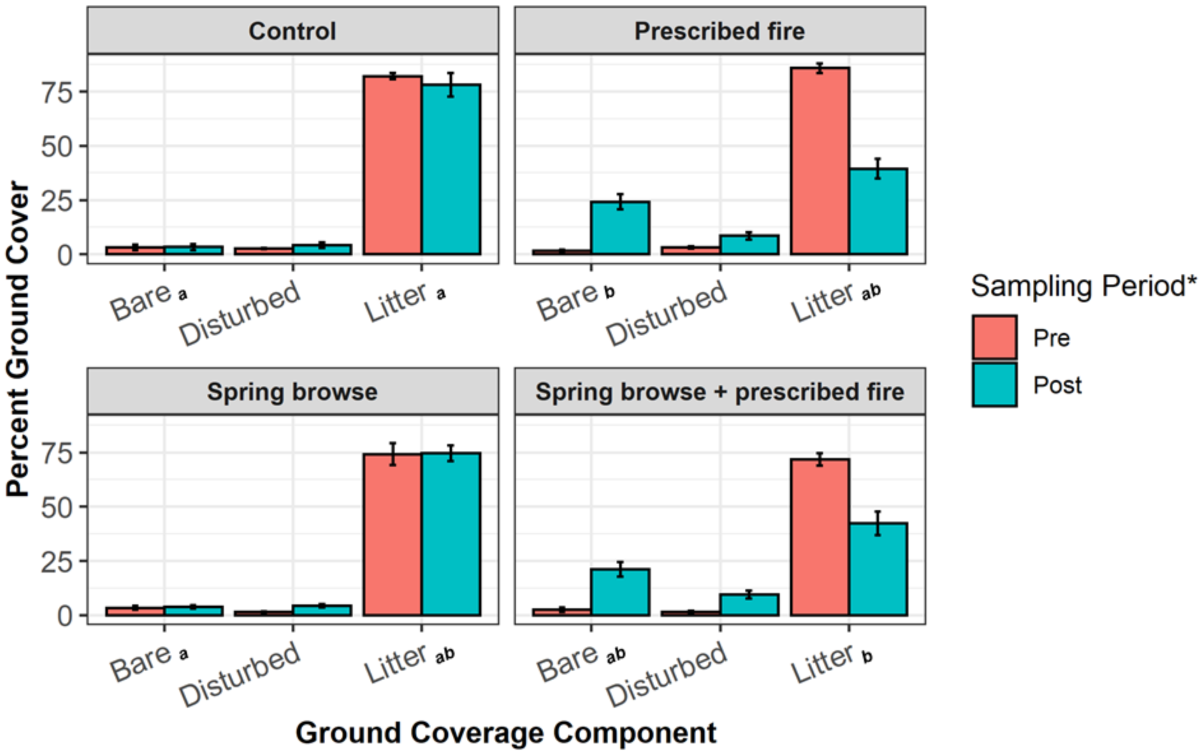
Control
Prescribed Fire
Spring Browse
Spring Browse + Prescribed Fire
Change in Midstory Trees per Hectare
600
300
0
-300
a
a
a
b
Cherries
Dogwoods
Eastern Redcedar
Elm-Hackberries
Hickories
Maples
Other Hardwoods
Red Oak
White Ash
White Oak
Species Group
Change in Understory Trees per Hectare
4000
2000
0
-2000
ab
b
ab
a

Figure 3



ALL
SB
Rx
SB & Rx
Treatment
-3
0
3
6
Cohen's D (95% CI)
Functional Group
Forb
Grass
Sedge
Legume
Shrub
Tree
Vine

Figure 4


Control
Prescribed fire
Spring browse
Spring browse + prescribed fire
Percent Ground Cover
75
50
25
0
Bare a
Disturbed
Litter a
Bare b
Litter ab
Bare a
Litter ab
Bare ab
Litter b
Ground Coverage Component
Sampling Period*
Pre
Post

Appendix A. Average percent cover for each functional group, ± the standard error. Data based on summer 2019 and 2020 sampling.

Treatment	Year	Forb	Grass	Sedge	Legume	Shrub	Tree	Vine
Control	2019	8.30 ± 1.4	5.3 ± 0.8	3.0 ± 0.5	6.0 ± 0.4	6.9 ± 0.9	14.9 ± 1.9	4.7 ± 0.5
	2020	10.8 ± 1.1	5.5 ± 1.2	4.4 ± 0.5	8.2 ± 1.5	11.3 ± 0.9	17.1 ± 3.1	7.3 ± 0.5
Spring browse	2019	7.2 ± 1.7	8.9 ± 1.2	2.0 ± 0.4	3.9 ± 0.5	6.0 ± 0.3	10.3 ± 0.07	6.2 ± 0.7
	2020	10.1 ± 1.5	14.6 ± 1.8	5.1 ± 1.1	6.1 ± 0.5	8.0 ± 1.1	16.0 ± 0.9	8.5 ± 1.3
Prescribed fire	2019	7.2 ± 0.8	5.7 ± 0.7	1.3 ± 0.3	4.8 ± 0.4	8.6 ± 0.5	22.5 ± 2.0	12.0 ± 2.2
	2020	16.5 ± 1.6	4.2 ± 1.2	1.7 ± 0.6	5.5 ± 1.2	9.2 ± 0.7	14.3 ± 2.0	9.5 ± 0.8
Spring browse + prescribed fire	2019	8.1 ± 2.5	7.4 ± 0.6	3.8 ± 0.9	9.0 ± 0.4	8.6 ± 0.6	14.3 ± 1.7	9.7 ± 1.8
	2020	19.0 ± 3.3	7.7 ± 2.0	5.0 ± 1.5	10.7 ± 1.7	11.0 ± 1.1	14.3 ± 2.11	13.1 ± 2.4

Appendix B. Cohen’s d, 95% upper confidence interval (CI), and 95% lower confidence interval values for the effect comparison analyses. Analyses include diversity and quality metrics, functional groups, and individual species for each treatment. All treatments are standardized to the control. Shaded cells indicate significance.

Analysis	Treatment	Cohen's d	CI lower	CI upper
Forbs	Prescribed fire	3.04	0.69	5.38
Forbs	Spring browse	1.02	-0.68	2.72
Forbs	Spring browse + prescribed fire	3.53	0.97	6.1
Forbs	All treatments	3.34	0.986	5.81
Grasses	Prescribed fire	1.10	-0.62	2.81
Grasses	Spring browse	2.82	0.56	5.08
Grasses	Spring browse + prescribed fire	1.40	-0.39	3.18
Grasses	All treatments	2.05	0.07	4.02
Sedges	Prescribed fire	0.66	-0.98	2.3
Sedges	Spring browse	1.13	-0.6	2.85
Sedges	Spring browse + prescribed fire	0.88	-0.8	2.56
Sedges	All treatments	0.95	-0.74	2.64
Shrubs	Prescribed fire	-1.25	-2.99	0.5
Shrubs	Spring browse	-0.61	-2.24	1.03
Shrubs	Spring browse + prescribed fire	-0.57	-2.2	1.06
Shrubs	All treatments	-0.87	-2.55	0.8
Trees	Prescribed fire	-3.31	-5.78	-0.85
Trees	Spring browse	1.05	-0.66	2.75
Trees	Spring browse + prescribed fire	-0.76	-2.41	0.9
Trees	All treatments	-1.23	-2.98	0.51
Vines	Prescribed fire	-1.52	-3.33	0.3
Vines	Spring browse	-0.35	-1.96	1.26
Vines	Spring browse + prescribed fire	0.46	-1.16	2.08
Vines	All treatments	-1.66	-3.52	0.19

Appendix C. Contact Information for Key Project Personnel

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Lauren S. Pile, USDA Forest Service, email: lauren.pile@usda.gov

We thank the Mark Twain National Forest, Northern Research Station, and Joint Fire Science Program for providing funding and expertise for this project. We also thank Trevor Ozier, Mike Kelly, Greg Painter, and Kimberly Bittle for getting fire on the ground; Loren Steele and Elizabeth Hamilton of Living Lands, LLC. for providing goats and guidance; Dacoda Maddox, Texas Nall, Eli Gaffney, Najwa Ghattas, Nathan Waller, and Carlee Steppe for field assistance.

Appendix D. List of Completed/Planned Scientific/Technical Publications/Science Delivery Products

Beebe, G., M.C. Stambaugh, L.S. Pile, B. Davidson, and D.C. Dey. In prep. Targeted browsing and prescribed fire for woodland management in Missouri, USA. Fire Ecology.

Beebe, G., L.S. Pile, M.C. Stambaugh, B. Davidson, and D.C. Dey. 2021. Can targeted browsing be a useful surrogate for prescribed fire? Fire Management Today 79:12-13.

Beebe, G. R., Pile, L., Stambaugh. M, Davidson, B., Dey, D. (2021, Feb.). Smoke, Goats, and Oaks: Effects of seasonal
targeted goat browsing prescriptions on woody reproduction density and floristic composition Ozark woodlands. Paper
presented at Oak Woodland and Forest Fire Consortium webinar series. Online.

Beebe, G. R., Pile, L., Stambaugh. M, Davidson, B., Dey, D. (2021, Jan.). Smoke, Goats, and Oaks: Effects of targeted goat
browsing and prescribed fire on woody regeneration, floristic composition, and fuel loading in an Ozark Hardwood
woodland. Paper presented at Oak Woodland and Forest Fire Consortium webinar series. Online.

Beebe, G. R., Pile, L., Stambaugh. M, Davidson, B., Dey, D. (2020, Feb.). Smoke, Goats, and Oaks: Targeted goat browsing
and prescribed fire as a means to halt woody encroachment and promote biodiversity in Ozark Hardwood Ecosystems.
Paper presented at the Missouri Natural Resources Conference. Osage Beach, MO.

Beebe, G. R., Pile, L., Stambaugh. M, Davidson, B., Dey, D. (2019, Nov.). Prescriptive goat browsing and prescribed fire as a
means to halt mesophication and promote biodiversity in Ozark Hardwood Ecosystems. Posted presented at the Missouri
Botanical Symposium. Rolla, MO.

Beebe, G. R., Pile, L., Stambaugh. M, Davidson, B., Dey, D. (2019, Oct). Prescriptive goat browsing and prescribed fire as a
means to halt mesophication and promote biodiversity in Ozark Hardwood Ecosystems. Poster presented at the Natural
Areas Conference. Pittsburgh, PA.

Beebe, G. R., Pile, L., Stambaugh. M, Davidson, B., Dey, D. (2019, July). Prescriptive goat browsing and prescribed fire as a
means to halt mesophication and promote biodiversity in Ozark Hardwood Ecosystems. Poster presented at the Fire in
Eastern Oaks Conference. State College, PA

Appendix E. Metadata

These data are archived on University of Missouri and USDA Forest Service computers controlled by the investigators. No deviations have been made from the original data management plan.